

Propaquizafop interactions with herbicides used in rice tolerant to ACCase inhibitors

Rafaella B. Mario^{a*}, Roberto C. A. Neto^a, Tilio A. Lucas^a, Simone Puntel^a, Leonardo S. Bolson^a, Pedro H. Folharini^a, Gabriel R. Rossato^a, André R. Ulguim^a

^a Federal University of Santa Maria, Rural Science Center, Department of Crop Protection, Santa Maria, RS, Brazil.

Abstract: An alternative for the control of weedy rice (*Oryza sativa*) and barnyardgrass (*Echinochloa* spp.) resistant to imidazolinone herbicides are acetyl coenzyme-A carboxylase inhibitors (ACCase) herbicides used in cultivar tolerant to these compounds. The objective was to evaluate the interaction of propaquizafop in tank mix with herbicides used in rice tolerant to ACCase inhibitors to control weedy rice and barnyardgrass. Two experiments were conducted, in the 2022/2023 season, in Dom Pedrito and Formigueiro. The hybrid XP739MA (MaxAce[®] technology) was used at both locations. The treatments were arranged in a 3x8+1 factorial design with factor A being rates of propaquizafop (0, 125 and 180 g ha⁻¹), and factor B tested herbicides carfentrazone, propanil, quinclorac, penoxsulam, florypyrauxifen-benzyl, bentazon, saflufenacil, and untreated

control. The additional treatment was two applications of propaquizafop (125 g ha⁻¹). The analyzed variables were weedy rice and barnyardgrass control, rice injury, yield components and yield. The interactions were mostly additive for weedy rice and barnyardgrass control. The antagonism of the tank mixture of propaquizafop with quinclorac and florypyrauxifen-benzyl for barnyardgrass and with propanil for weedy rice reduced the yield components in Dom Pedrito. The interactions of propaquizafop with propanil were antagonistic and resulted in the lowest yield in Formigueiro. For this tank mix at the highest propaquizafop rate, yield decreased 14.6% more than at the 125 g ha⁻¹ rate. Tank mix of propaquizafop with other herbicides used in tolerant rice with MaxAce[®] technology can be used, increasing the weed control spectrum.

Keywords: Colby; Tank Mix; Antagonism; Additivity; MaxAce[®]

Journal Information:

ISSN - 2675-9462

Website: <http://awsjournal.org>

Journal of the Brazilian Weed
Science Society

How to cite: Mario RB, Neto RCA, Lucas TA, Puntel S, Bolson LS, Folharini PH, Rossato GR, Ulguim AR. Propaquizafop interactions with herbicides used in rice tolerant to ACCase inhibitors. Adv Weed Sci. 2025;43:e020250096.

<https://doi.org/10.51694/AdvWeedSci/2025;43:00011>

Approved by:

Editor in Chief: Carol Ann Mallory-Smith

Associate Editor: Nilda Roma-Burgos

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Received: October 15, 2024

Approved: February 4, 2025

*** Corresponding author:**

<rafaella.boemo@gmail.com>



This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided that the original author and source are credited.

Copyright: 2022

1. Introduction

Rice is the staple food of more than three billion people and is essential for the subsistence of communities around the world. It serves low-income families, who depend on it as a primary source of energy and nutrients, to those with greater economic power, where it appears as an ingredient in elaborate and traditional dishes. Its relevance goes beyond nutrition, playing a fundamental role in the culture, economy and food security of countless nations. It is the second most consumed cereal in the world, behind only corn, and stands out for its adaptability to different climates and cultivation systems. In Brazil, rice has a special place in the population's daily diet, with a significant total production of 9.2 million tons in the 2022/23 session (Companhia Nacional de Abastecimento, 2023). This performance not only reinforces the importance of rice for the country's agricultural economy, but also for national food security, ensuring the food supply for millions of homes.

Among the factors that interfere with crop yield, competition with weeds can cause significant yield losses, while weeds also serve as hosts for pests and diseases (Agostinetto et al., 2022). The main weeds present in flooded rice in Rio Grande do Sul (RS) are weedy rice (*Oryza sativa*), barnyardgrass (*Echinochloa* spp.) and sedges (*Cyperus* spp.) (Fruet et al., 2020; Silva et al., 2020). Yield reductions in flooded rice can reach 600 kg ha⁻¹ due to competition with barnyardgrass (Richter et al., 2019). Furthermore, the competition for nutrients between barnyardgrass and flooded rice in the vegetative phase is greater for nitrogen (N), and in the reproductive phase for potassium (K), calcium (Ca) and magnesium (Mg), with each barnyardgrass plant m⁻² capable of reducing rice yield by 1.13% (Ulguim et al., 2020).

Weedy rice stands out as a problematic weed species in flooded rice due to its taxonomic similarity to rice, making it difficult to control with selective herbicides. It constitutes a serious problem, with only a few chemical control alternatives before and after crop emergence, which can reduce grain yield and quality. In more drastic situations, fields are abandoned due to high infestations of the weed (Silva et al., 2021). To promote the selective control of weedy rice, genotypes have been commercialized with tolerance to herbicides that are naturally non-selective to the *Oryza* genus such as imidazolinones (inhibition of acetolactate synthase – ALS) and aryloxyphenoxy-propionates (inhibition of acetyl coenzyme-A carboxylase – ACCase).

The Clearfield (CL) technology was launched in Brazil in 2003, through rice cultivars with a gene for tolerance to herbicides from the imidazolinone (IMI) chemical family of Group 2 herbicides (Avila et al., 2021). Due to inadequate use and minimal implementation of stewardship recommendations, the evolution of herbicide-resistant biotypes of weedy rice was inevitable. The monoculture of the CL system for more than six consecutive years, the use of herbicides with the same mechanism of action and the use of rates greater than 1.5x above the label rate, increased the selection pressure for weed resistance, reducing the efficacy of the technology in rice production areas (Ulguim et al., 2019). Five IMI-resistant weed species are currently documented in flooded rice crops in southern Brazil, including weedy rice and barnyardgrass (Heap, 2024).

An alternative for controlling IMI-resistant weedy rice and barnyardgrass is the technology of rice genotypes with tolerance to herbicides of ACCase inhibitors. In Brazil, this technology was commercially launched in the 2022/2023 growing season, with tolerance to propaquizafop and quizalofop herbicides in the Max-Ace® and Provisia®, respectively (RiceTec, 2024; BASF Corporation, 2024). Both were obtained through an induced mutation, in which Max-Ace® presents a change from a serine to a glycine at position 2096 (mutation G2096S) in ACCase makes the enzyme tolerant/resistant to some herbicides, including propaquizafop (Hinga et al., 2016). However, these herbicides have a spectrum limited to plants of the Poaceae family only (Hinga et al., 2016).

There is still a need for chemical control alternatives for eudicotyledonous and sedge weed species in rice production. The tank mixing of herbicides is a common practice, used by 97% of producers in Brazil (Gazziero, 2015), and practiced by 65% of farmers in rice fields (Fruet et al., 2020). This practice, in addition to increasing the control spectrum, also reduces application costs and optimizes land management (Bianchi et al., 2020). Therefore, understanding the effect of ACCase inhibitor herbicides in tank mix with other herbicides is necessary to optimize weed management in flooded rice tolerant to ACCase inhibitor herbicides.

The interaction of quizalofop when mixed with florypyrauxifen-benzyl is additive for the control of barnyardgrass, being a tank mix option to broaden the spectrum of weed control (Sanders et al., 2021). However, there is little information on the tank mix of herbicides with propaquizafop, used in Max-Ace® technology in Brazil. Therefore, the objective of this study was to evaluate the interaction of propaquizafop in tank mix with herbicides used in rice tolerant to ACCase inhibitors to control weedy rice and barnyardgrass.

2. Material and Methods

Two experiments were conducted, in the 2022/2023 season, in two sites: Dom Pedrito (30°58'54"S 54°40'39"W) and Formigueiro (30°0'32"S 53°29'54"W), located in Rio

Grande do Sul, Brazil. The design used was randomized blocks, with four replications, in 3x5m plots. The soil in both sites is classified as Alfisols (United States Department of Agriculture, 2024). The state's climate, according to the Köppen classification, is characterized as subtropical (Cfa), with hot summers and no defined dry season (Alvares et al., 2013).

Rice was planted on October 5, 2022 in Dom Pedrito and on November 10, 2022 in Formigueiro, using the early maturity hybrid XP739MA (Max-Ace® technology), at 45 kg ha⁻¹. Rice was fertilized based on research recommendations. In Dom Pedrito 20 kg ha⁻¹ of N, 104 kg ha⁻¹ of P₂O₅ were applied at sowing. Topdressing 120 kg ha⁻¹ of K₂O and 135 kg ha⁻¹ of N, divided into two applications, the first in the phenological stages in V₃/V₄ and the second in R₀ (Counce et al., 2000). In Formigueiro 18 kg ha⁻¹ of N, 70 kg ha⁻¹ of P₂O₅ and 70 kg ha⁻¹ of K₂O was applied at sowing. Topdressing 108 kg ha⁻¹ of N, divided into two applications, in V₃/V₄ e R₀.

In both locations, 25 treatments were tested (Table 1). The herbicides were applied before flood irrigation, when the rice was at the V₃/V₄ stage. The treatments were arranged in a 3x8+1 factorial design, with factor A being the rates of propaquizafop (0, 125 and 180 g ha⁻¹) and factor B was herbicides in tank mixes. The herbicides added to propaquizafop were: carfentrazone, propanil, quinclorac, penoxsulam, florypyrauxifen-benzyl, bentazon, saflufenacil, and no additional herbicide (Table 1). The nontreated check had no propaquizafop and no other herbicide. The additional treatment consisted of two applications of propaquizafop alone at 125 g ha⁻¹, as specified on the herbicide label (Adama Brasil S/A, 2024). The first propaquizafop application was at the V₃/V₄ stage of rice before flooding, and the second was 15 days after the first.

The herbicides were applied using a backpack sprayer, pressurized with CO₂ and a handheld spray boom with four 110.015 flat-fan nozzles spaced 0.5 m apart. The equipment was calibrated to deliver 150 L ha⁻¹. Flood irrigation was initiated two days after herbicide, and the water level remained stable after eight days. At the time of application, Dom Pedrito had weedy rice and barnyardgrass infestations of 11 and 8 plants m⁻², respectively, at the 5–8 leaf stage. In Formigueiro, barnyardgrass infestation was at 224 plants m⁻² (6–8 leaves), while weedy rice was at 56 plants m⁻² (4–6 leaves).

Rice injury and weed control was evaluated visually by two personnel together, based on a rating scale of 0 to 100 where 0 = absence of symptoms and 100 = death. Evaluations were done at 10, 20 and 30 days after application (DAA), for both locations. Rice was harvested on February 28 and March 14, 2023 in Dom Pedrito and Formigueiro, respectively.

Rice was harvested from 6 m² area. Samples were threshed, their weight corrected to 13% moisture content, and yields converted to kg ha⁻¹. In Dom Pedrito, the yield for the untreated check and the zero rate of propaquizafop was estimated visually and based on treatments with single herbicides (without propaquizafop), as these plots

Table 1 - Herbicides used in tank mix with propaquizafop in irrigated rice field experiment and their respective rate of active ingredient (a.i). Dom Pedrito-RS and Formigueiro-RS, 22/23 season

Active ingredient	Trade name	Manufactory	Formulation	g a.i. ha ⁻¹
Saflufenacil ¹	Heat	BASF	WG ²	70
Bentazon ¹	Basagran	BASF	SL ³	1200
Florpyrauxifen-benzyl	Loyant	Corteva	EC ⁴	30
Penoxsulam ¹	Ricer	Corteva	SC ⁵	60
Quinclorac ¹	Facet	BASF	WP ⁶	375
Propanil ¹	Stam	UPL	WG ²	2800
Carfentrazone ¹	Aurora	FMC	EC ⁴	40
Propaquizafop ¹	Acert	ADAMA	EC ⁴	125
Propaquizafop ¹	Acert	ADAMA	EC ⁴	180

¹ Mineral oil adjuvant added in a 0.5 v/v. ² dispersible granules; ³ soluble concentrates; ⁴ emulsifiable concentrates; ⁵ suspension concentrates; ⁶ wet-table powders

could not be harvested due to severe weed infestation. Additionally, the number of panicles m⁻², grains per panicle, and 1,000-grain weight were evaluated. Panicles were counted directly, grains per panicle were averaged from 10 randomly collected panicles per plot, and 1,000-grain weight was determined using five replicates of 100 grains, corrected to 13% moisture content.

The variables were analyzed with R software (R Core Team, 2019). Using the ExpDes.pt package (Healy, 1956), subjected to analysis of variance, homogeneity of residual variances (Barlett) e normality of errors (Shapiro-Wilk). When the factor effect was significant, means were compared using the Scott-Knott test ($p \leq 0.05$). For the additional treatment, a Dunnett test was performed, comparing the tank mix with it. Weed control data were used to test for herbicide interactions following the Colby (1967) methodology, which consists of evaluating the effect of herbicides alone and in tank mix. Equation 1 gives the expected control value of the tank mix, obtained from the control of each herbicide alone, and compared with the observed value of the tank mix.

$$E = 100 - \{[(100-X) \cdot (100-Y)] / 100\} \quad (1)$$

where: E = expected value of the herbicide tank mix in each combination; X and Y = control. If the observed control is greater than expected, the interaction is synergistic, if the observed control is equal to the sum of the two alone herbicides, the interaction is additive, and if the observed control is less than expected, the interaction is antagonistic (Colby, 1967). The interactions were compared by Student's t-test ($p \leq 0.05$).

3. Results and discussion

The data were adjusted to the requirements of homogeneity (Barlett) and normality (Shapiro-Willk) tests.

The interaction effect between propaquizafop rate and tank mix partner, was significant at Formigueiro and Dom Pedrito for the number of panicles m⁻², weight of 1,000-grain and yield, and number of grains panicle⁻¹ in Formigueiro but not in Dom Pedrito. Rice injury was similar across herbicide treatments, not exceeding 15% (data not shown).

For the weedy rice control in Dom Pedrito, the activity of herbicides in mixtures were mainly additive (Table 2). Overall and across the three evaluation periods, 64% of the comparisons between the observed and estimated control using the Colby test showed additive interactions, while 36% were antagonistic, and none were synergistic. At 30 DAA there was antagonism of the mixtures of propaquizafop with propanil and carfentrazone at a rate of 125 g ha⁻¹, and with bentazon and propanil at a rate of 180 g ha⁻¹ (Table 2). In Formigueiro, in the weedy rice control, there was antagonism only with the tank mix of propaquizafop with propanil in all evaluation periods for both rates (Table 3).

Similar results were found in other studies published in the literature, where tank mix of herbicides such as propanil, penoxsulam and quinclorac with quizalofop resulted in antagonism (Lancaster et al., 2019). The tank mix of quizalofop with propanil and quinclorac was antagonistic of barnyardgrass and weedy rice control, resulting in control 7 to 20% lower than the expected values calculated from the results of the herbicides applied alone (Lancaster et al., 2019).

For barnyardgrass control in Dom Pedrito and Formigueiro 26% of the interactions were considered antagonistic (Tables 4 and 5). Thus, around 16% and 14% antagonistic interactions for Dom Pedrito and Formigueiro, respectively, resulting from the tank mix at the highest rate of propaquizafop (180 g ha⁻¹). The result is justified by propaquizafop alone had high control and expected value for Colby's test is higher than that of the 125 g ha⁻¹ rate (Tables 4 and 5). Furthermore, for barnyardgrass control at 30 DAA

Table 2 - Weedy rice control (%) observed and expected by the Colby test, evaluated at 10, 20 and 30 days after application (DAA), using mixtures of different herbicides with propaquizafop at doses of 125 and 180 g ha⁻¹. Dom Pedrito, 22/23 season

Herbicides ¹	Control (%)				
	Propaquizafop (g ha ⁻¹)				
	0	125	180		
	Observed	Observed	Expected	Observed	Expected
10DAA					
Untreated	0	90	-	95	-
Bentazon	0	80 ^{ns}	90	92 ^{ns}	95
Florpyrauxifen	5	86 ^{ns}	91	94 ^{ns}	95
Penoxsulam	0	94 ^{ns}	90	92 ^{ns}	95
Quinclorac	0	88 ^{ns}	90	93 ^{ns}	95
Propanil	0	53 [*]	90	74 [*]	95
Carfentrazone	10	89 ^{ns}	92	84 ^{ns}	95
Saflufenacil	4	87 ^{ns}	91	89 ^{ns}	95
20DAA					
Untreated	0	95	-	96	-
Bentazon	0	94 ^{ns}	98	97 ^{ns}	99
Florpyrauxifen	0	96 [*]	99	91 [*]	99
Penoxsulam	0	97 ^{ns}	99	95 ^{ns}	99
Quinclorac	0	95 [*]	99	95 [*]	99
Propanil	0	88 [*]	98	93 [*]	99
Carfentrazone	0	94 [*]	99	93 [*]	99
Saflufenacil	0	94 ^{ns}	98	94 [*]	98
30DAA					
Untreated	0	92	-	99	-
Bentazon	0	92 ^{ns}	92	96 [*]	99
Florpyrauxifen	0	98 ^{ns}	98	97 ^{ns}	99
Penoxsulam	0	92 ^{ns}	98	99 ^{ns}	99
Quinclorac	0	98 ^{ns}	98	96 ^{ns}	99
Propanil	0	72 [*]	92	79 [*]	99
Carfentrazone	0	93 [*]	98	96 ^{ns}	99
Saflufenacil	0	98 ^{ns}	98	98 ^{ns}	99

^{ns} indicate no significant differences according to the Colby test ($p \leq 0.05$) based on the Student's t-test, with the herbicide interaction considered additive.

^{*} indicate significant differences according to the Colby test ($p \leq 0.05$) based on the Student's t-test, with the interaction considered antagonistic if the observed control was lower than expected. ¹ The herbicides were applied at the recommended rates for flooded rice, at the V₃/V₄ stage of rice, before flooding.

there was antagonism only of propaquizafop mixed with propanil, in the two rates of the first herbicide (Tables 4 and 5), as was observed for weedy rice (Tables 2 and 3).

The tank mix of propaquizafop and propanil should not be recommended for controlling weedy rice, possibly because they have different modes of action on the plant. The antagonism can be explained due to systemic translocation for propaquizafop and effect of contact for propanil. Tank mix of cyhalofop-butyl and propanil for control of barnyardgrass were antagonistic, because propanil reduced the rate of metabolism of cyhalofop-butyl by decreasing the apoplastic esterase enzyme that converts cyhalofop-butyl to cyhalofop-acid (Ottis et al., 2005).

For both sites, the tank mix of propaquizafop with penoxsulam was antagonistic for barnyardgrass control

only in the evaluation at 20 DAA (Tables 4 and 5). For the barnyardgrass control in both sites, there was antagonism of the tank mix of propaquizafop with florpyrauxifen and quinclorac in general until the evaluation at 20 DAA (Tables 4 and 5). As observed for weedy rice, this result may be associated with the mode of action of the quinclorac and florpyrauxifen herbicides.

The antagonistic interaction of propaquizafop with florpyrauxifen is expected because this herbicide belongs to the mode of action of auxin mimics, with reports in the literature of antagonism of these tank mix (Barbieri et al., 2022). An example is tank mix of clethodim and 2,4-D that resulted in an antagonistic effect for ryegrass control, but an increase in the rate of clethodim compensated for the antagonism with 2,4-D (Polito et al., 2021). However,

Table 3 - Weedy rice control (%) observed and expected by the Colby test, evaluated at 10, 20 and 30 days after application (DAA), using tank mix of different herbicides with propaquizafop at doses of 125 and 180 g ha⁻¹. Formigueiro, 22/23 season

Herbicides ¹	Control (%)				
	Propaquizafop (g ha ⁻¹)				
	0	125	180		
	Observed	Observed	Expected	Observed	Expected
10DAA					
Untreated	0	99	-	99	-
Bentazon	0	99 ^{ns}	99	99 ^{ns}	99
Florpyrauxifen	0	99 ^{ns}	99	99 ^{ns}	99
Penoxsulam	0	96 ^{ns}	99	96 ^{ns}	100
Quinclorac	0	99 ^{ns}	99	90 ^{ns}	99
Propanil	0	58 *	99	50 *	99
Carfentrazone	0	99 ^{ns}	99	99 ^{ns}	99
Saflufenacil	0	99 ^{ns}	99	99 ^{ns}	99
20DAA					
Untreated	0	97	-	100	-
Bentazon	0	97 ^{ns}	97	98 ^{ns}	100
Florpyrauxifen	0	97 ^{ns}	97	99 ^{ns}	100
Penoxsulam	25	86 ^{ns}	97	94 ^{ns}	100
Quinclorac	0	99 ^{ns}	97	99 ^{ns}	100
Propanil	0	75 *	97	50 *	100
Carfentrazone	0	99 ^{ns}	97	98 ^{ns}	100
Saflufenacil	0	99 ^{ns}	97	98 ^{ns}	100
30DAA					
Untreated	0	93	-	98	-
Bentazon	0	95 ^{ns}	93	97 ^{ns}	98
Florpyrauxifen	41	97 ^{ns}	96	100 ^{ns}	99
Penoxsulam	0	93 ^{ns}	93	97 ^{ns}	98
Quinclorac	19	96 ^{ns}	95	99 ^{ns}	98
Propanil	0	40 *	93	63 *	98
Carfentrazone	0	97 ^{ns}	93	98 ^{ns}	98
Saflufenacil	0	99 ^{ns}	93	98 ^{ns}	98

^{ns} indicate no significant differences according to the Colby test ($p \leq 0.05$) based on the Student's t-test, with the herbicide interaction considered additive.

* indicate significant differences according to the Colby test ($p \leq 0.05$) based on the Student's t-test, with the interaction considered antagonistic if the observed control was lower than expected. ¹ The herbicides were applied at the recommended rates for flooded rice, at the V₃/V₄ stage of rice, before flooding.

as seen previously, the same was not observed for weedy rice control for tank mix of propaquizafop with florpyrauxifen, since even increasing the rate of propaquizafop the antagonism was not overcome.

The number of panicles m⁻² in Dom Pedrito, the highest number was obtained with the tank mix of propaquizafop at a rate of 125 g ha⁻¹ with carfentrazone (Figure 1). At the highest rate (180 g ha⁻¹), the tank mix with carfentrazone, bentazon and quinclorac were superior to the other treatments (Figure 1). These mixtures had control above 96% at 30 DAA for weedy rice and barnyardgrass (Tables 2 and 4). For the variable 1000-grain weight the tank mix with propanil at a rate of 125 g ha⁻¹ resulted in the lowest values (Figure 2). For the highest rate of propaquizafop, no difference was observed between treatments. These

results corroborate the control data, where the observed antagonism of the tank mix of propaquizafop with quinclorac and florpyrauxifen for barnyardgrass (Tables 4 and 5) and with propanil for weedy rice (Tables 2 and 3) reduced the yield components (Figures 1 and 2).

Grain yield in Dom Pedrito presented in a significant interaction between the tank mix and the rates of propaquizafop (Figure 3). Propaquizafop at 125 g ha⁻¹, the tank mix with bentazon, quinclorac and propanil resulted in lower yield than the other treatments. At the highest rate of propaquizafop, there was no statistical difference between the treatments (Figure 3). Herbicide treatments without a tank mix partner to control barnyardgrass and weedy rice resulted in low yields similar to, or lesser than, those of antagonistic

Table 4 - Barnyardgrass control (%) observed and expected by the Colby test, evaluated at 10, 20 and 30 days after application (DAA), using tank mix of different herbicides with propaquizafop at doses of 125 and 180 g ha⁻¹. Dom Pedrito, 22/23 season

Herbicides ¹	Control (%)				
	Propaquizafop (g ha ⁻¹)				
	0	125		180	
	Observed	Observed	Expected	Observed	Expected
10DAA					
Untreated	0	90	-	96	-
Bentazon	0	90 ^{ns}	94	93 ^{ns}	96
Florpyrauxifen	80	95 ^{ns}	99	95 *	99
Penoxsulam	75	88 ^{ns}	97	95 ^{ns}	98
Quinclorac	73	81 ^{ns}	95	94 ^{ns}	97
Propanil	25	30 *	95	93 ^{ns}	96
Carfentrazone	13	91 ^{ns}	94	89 ^{ns}	96
Saflufenacil	0	94 ^{ns}	94	93 ^{ns}	96
20 DAA					
Untreated	0	94	-	97	-
Bentazon	65	98 ^{ns}	97	95 ^{ns}	98
Florpyrauxifen	90	97 ^{ns}	99	97 ^{ns}	99
Penoxsulam	90	95 ^{ns}	99	95 *	99
Quinclorac	90	93 *	99	95 *	99
Propanil	85	45 *	95	90 *	99
Carfentrazone	58	95 ^{ns}	96	91 *	99
Saflufenacil	80	94 ^{ns}	99	93 *	99
30 DAA					
Untreated	0	99	-	99	-
Bentazon	0	97 ^{ns}	99	97 ^{ns}	99
Florpyrauxifen	99	99 ^{ns}	100	97 ^{ns}	100
Penoxsulam	89	96 ^{ns}	100	97 ^{ns}	100
Quinclorac	92	93 ^{ns}	100	98 ^{ns}	100
Propanil	70	70 *	100	91 *	100
Carfentrazone	0	95 ^{ns}	99	99 ^{ns}	99
Saflufenacil	0	99 ^{ns}	99	98 ^{ns}	99

^{ns} indicate no significant differences according to the Colby test ($p \leq 0.05$) based on the Student's t-test, with the herbicide interaction considered additive. * indicate significant differences according to the Colby test ($p \leq 0.05$) based on the Student's t-test, with the interaction considered antagonistic if the observed control was lower than expected. ¹ The herbicides were applied at the recommended rates for flooded rice, at the V₃/V₄ stage of rice, before flooding.

treatments, since these herbicides have a control spectrum mainly in eudicotyledonous plants.

It is important to highlight that knowledge of antagonistic tank mix for the of weedy rice control is extremely important in the context of flooded rice production (Tables 2 and 3). The herbicide propaquizafop provides effective of weedy rice control, making it an important tool for managing this species, given the challenges of selective control (Avila et al., 2021). This difficulty lies in the fact that the weed and crop belong to the same species, whose crop tolerance to propaquizafop occurs through induced mutation events (Hinga et al., 2016). Therefore, failures in weedy rice control in flooded rice may favor the occurrence of gene flow from cross-pollination of tolerant cultivars

and the weed (Menezes et al., 2009). This fact can result in rapid evolution of herbicide resistance in commercial grain production areas, as observed for CL rice (Goulart et al., 2014). Therefore, such antagonism results may imply loss of crop yield, with an impact on rice yield components.

The tank mix of propaquizafop (125 g ha⁻¹) with bentazon produced the highest number of panicles m⁻² in Formigueiro (Figure 4). At higher propaquizafop rates, only the mix with propanil led to fewer panicles m⁻². The number of grains panicle⁻¹ was lower than the untreated check when propaquizafop (125 g ha⁻¹) was combined with quinclorac, florpyrauxifen, propanil and penoxsulam (Figure 5). For propaquizafop at 180 g ha⁻¹, only the tank mix with propanil was lower than the untreated

Table 5 - Barnyardgrass control (%) observed and expected by the Colby test, evaluated at 10, 20 and 30 days after application (DAA), using tank mix of different herbicides with propaquizafop at doses of 125 and 180 g ha⁻¹. Formigueiro, 22/23 season

Herbicides ¹	Control (%)				
	Propaquizafop (g ha ⁻¹)				
	0	125	180		
	Observed	Observed	Expected	Observed	Expected
10DAA					
Untreated	0	99	-	99	-
Bentazon	0	99 ^{ns}	99	99 ^{ns}	99
Florpyrauxifen	45	99 ^{ns}	99	99 *	99
Penoxsulam	3	90 ^{ns}	99	90 ^{ns}	99
Quinclorac	58	80 *	100	75 *	100
Propanil	5	40 *	99	43 *	99
Carfentrazone	5	98 ^{ns}	99	99 ^{ns}	99
Saflufenacil	5	97 ^{ns}	99	99 ^{ns}	99
20 DAA					
Untreated	0	99	-	100	-
Bentazon	0	97 ^{ns}	99	97 ^{ns}	100
Florpyrauxifen	55	98 ^{ns}	100	98 ^{ns}	100
Penoxsulam	32	87 *	99	90 ^{ns}	100
Quinclorac	64	91 ^{ns}	100	89 *	100
Propanil	14	43*	99	31 *	100
Carfentrazone	0	99 ^{ns}	99	98 ^{ns}	100
Saflufenacil	3	98 ^{ns}	99	99 ^{ns}	100
30 DAA					
Untreated	0	100	-	100	-
Bentazon	0	100 ^{ns}	100	100 ^{ns}	100
Florpyrauxifen	90	100 ^{ns}	100	100 ^{ns}	100
Penoxsulam	13	94 ^{ns}	100	100 ^{ns}	100
Quinclorac	77	100 ^{ns}	100	100 ^{ns}	100
Propanil	13	70 *	100	21 *	100
Carfentrazone	0	100 ^{ns}	100	100 ^{ns}	100
Saflufenacil	0	100 ^{ns}	100	100 ^{ns}	100

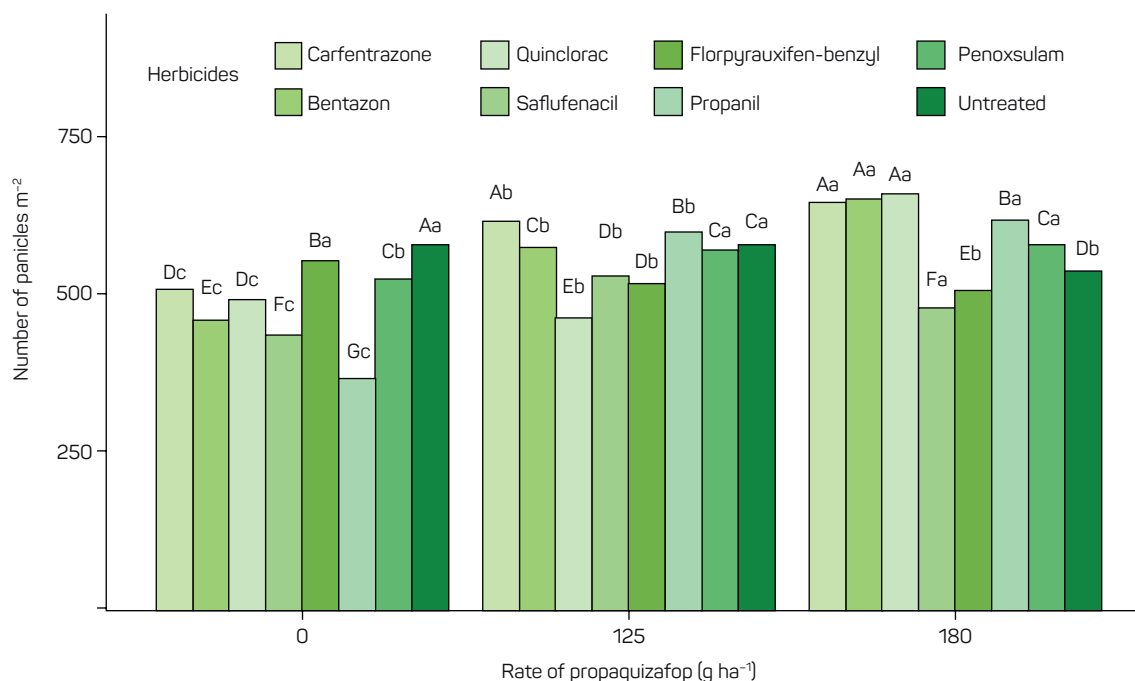
^{ns} indicate no significant differences according to the Colby test ($p \leq 0.05$) based on the Student's t-test, with the herbicide interaction considered additive. * indicate significant differences according to the Colby test ($p \leq 0.05$) based on the Student's t-test, with the interaction considered antagonistic if the observed control was lower than expected. ¹ The herbicides were applied at the recommended rates for flooded rice, at the V₃/V₄ stage of rice, before flooding.

check. The 1000-grain weight in Formigueiro did not differ between the treatments with of propaquizafop at 125 g ha⁻¹ (Figure 6).

The tank mix of quizalofop with penoxsulam resulted in antagonism for barnyardgrass control, showing an 8% reduction in control when compared to quizalofop alone (Lancaster et al., 2019). Then, the sequential application of propaquizafop as labeled recommended is important to control possible failures and new weed plant emergence flows, preserving the technology. In the present study, sequential application was only used in the additional treatment, in order to evaluate the differences in the other treatments by mixing the herbicides only, since sequential application would result in the control of all plots.

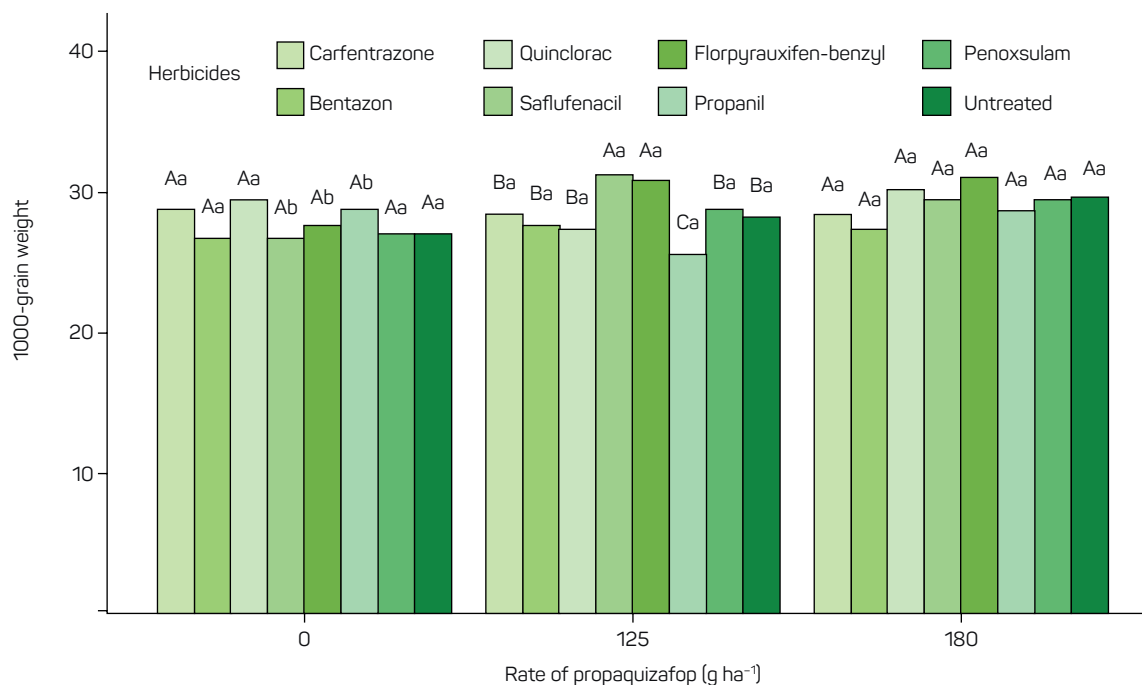
The tank mix of propanil and propaquizafop in Formigueiro resulted in lower grain yield than other treatments including untreated check (Figure 7). For this tank mix at the highest rate of propaquizafop the yield reduces 14.6% more than 125 g ha⁻¹ rate (Figure 7). It is worth noting that yield values close to zero when applying the alone herbicides are due to the fact that competition with barnyardgrass and weedy rice.

The Dunnet test was used to compare the treatments with the additional treatment for the yield variable (Figure 8 and 9). The additional treatment consists of the sequential application of propaquizafop, following the recommendations for the use of Max-Ace® technology (Adama Brasil, 2024).



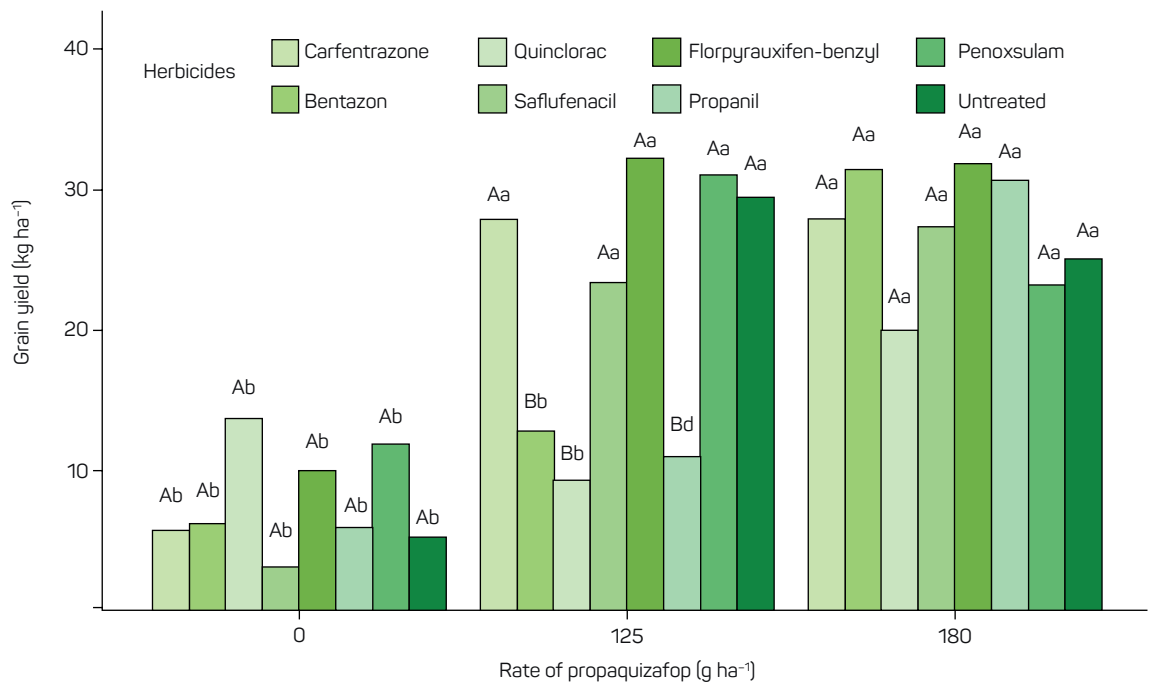
Means followed by the same letter do not differ from each other according to the Scott-Knott test ($p \leq 0.05$). Uppercase letters compare herbicides within the same dose of propaquizafop; lowercase letters compare propaquizafop doses for a given herbicide

Figure 1 - Number of panicles m⁻² of irrigated rice subjected to the application of three doses of propaquizafop in a tank mix with different herbicides. Dom Pedrito, 22/23 season



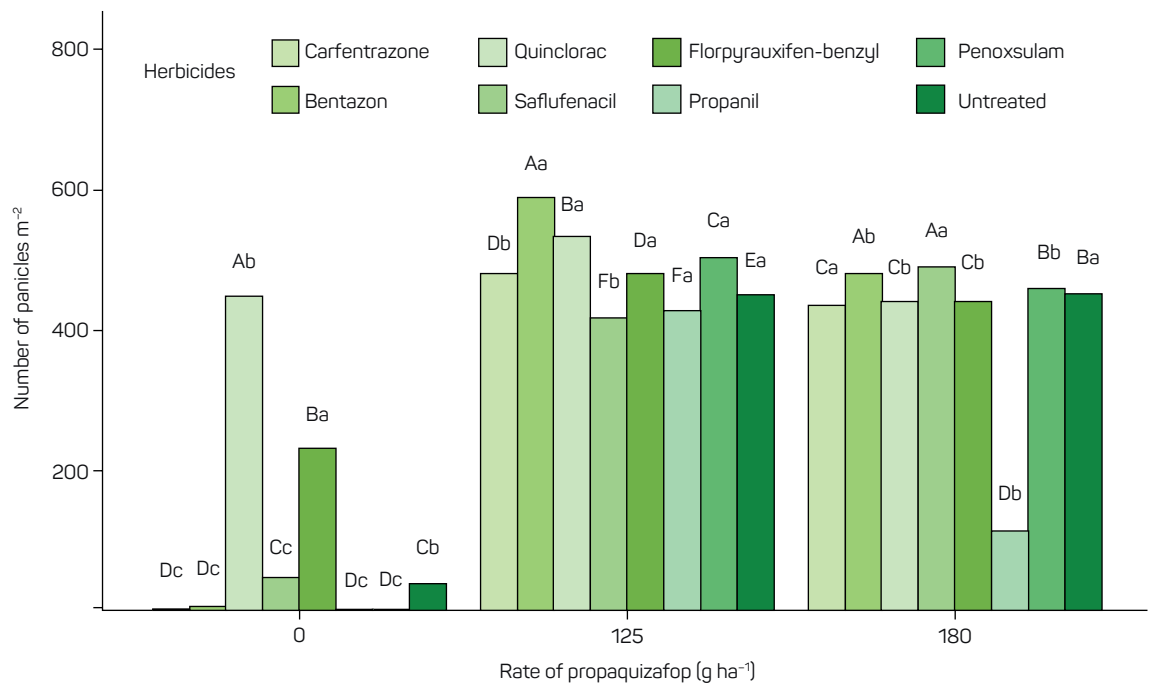
Means followed by the same letter do not differ from each other according to the Scott-Knott test ($p \leq 0.05$). Uppercase letters compare herbicides within the same dose of propaquizafop; lowercase letters compare propaquizafop doses for a given herbicide

Figure 2 - 1,000-grain weight (g) of irrigated rice subjected to the application of three doses of propaquizafop in a tank mix with different herbicides. Dom Pedrito, 22/23 season



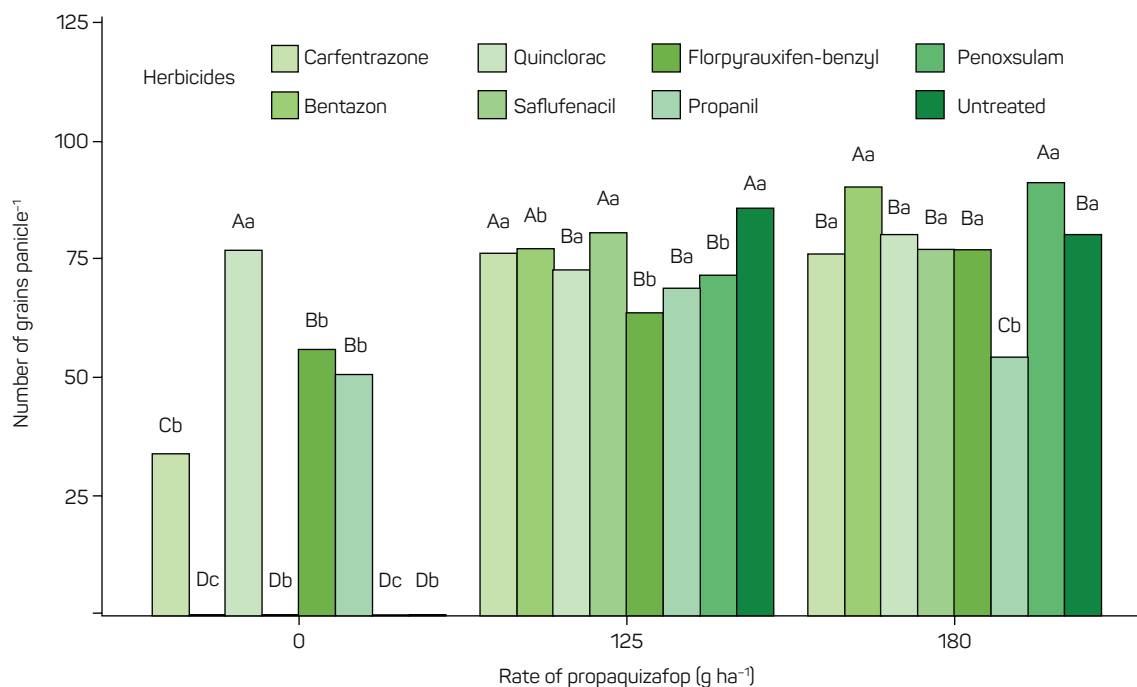
Means followed by the same letter do not differ from each other according to the Scott-Knott test ($p \leq 0.05$). Upper case letters compare herbicides within the same dose of propaquizafop; lower case letters compare propaquizafop doses for a given herbicide

Figure 3 - Grain yield (kg ha⁻¹) of irrigated rice subjected to the application of three doses of propaquizafop in a tank mix with different herbicides. Dom Pedrito, 22/23 season



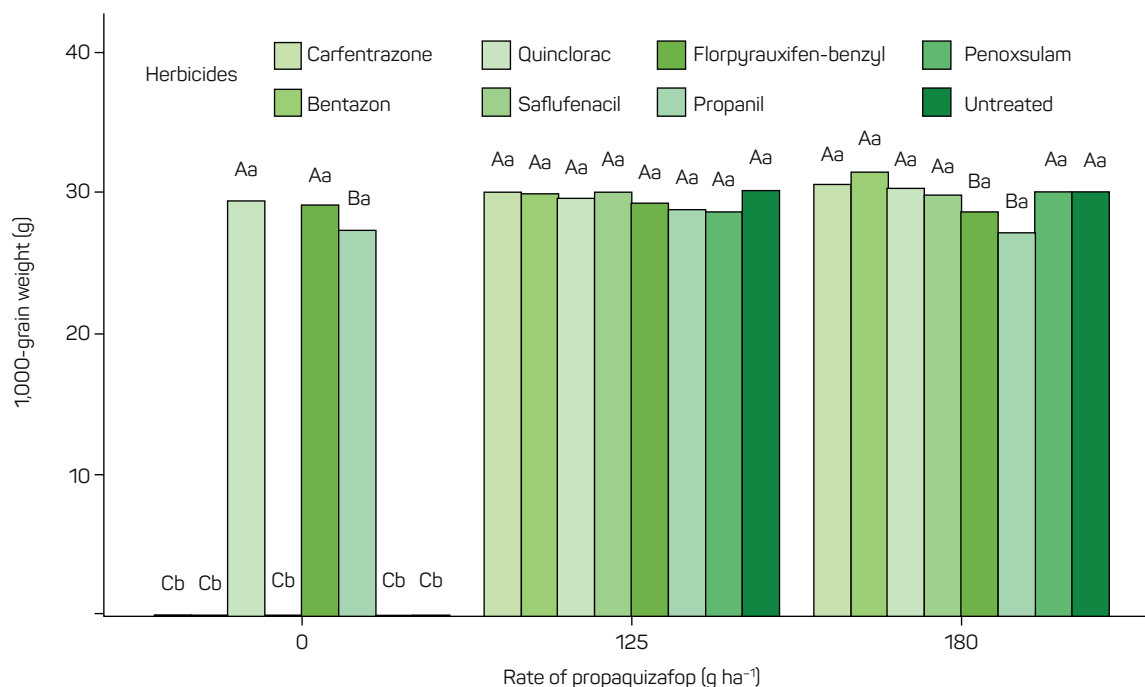
Means followed by the same letter do not differ from each other according to the Scott-Knott test ($p \leq 0.05$). Upper case letters compare herbicides within the same dose of propaquizafop; lower case letters compare propaquizafop doses for a given herbicide

Figure 4 - Number of panicles m⁻² of irrigated rice subjected to the application of three doses of propaquizafop in a tank mix with different herbicides. Formigueiro, 22/23 season



Means followed by the same letter do not differ from each other according to the Scott-Knott test ($p \leq 0.05$). Uppercase letters compare herbicides within the same dose of propaquizafop; lowercase letters compare propaquizafop doses for a given herbicide

Figure 5 - Number of grains panicle⁻¹ of irrigated rice subjected to the application of three doses of propaquizafop in a tank mix with different herbicides. Formigueiro, 22/23 season



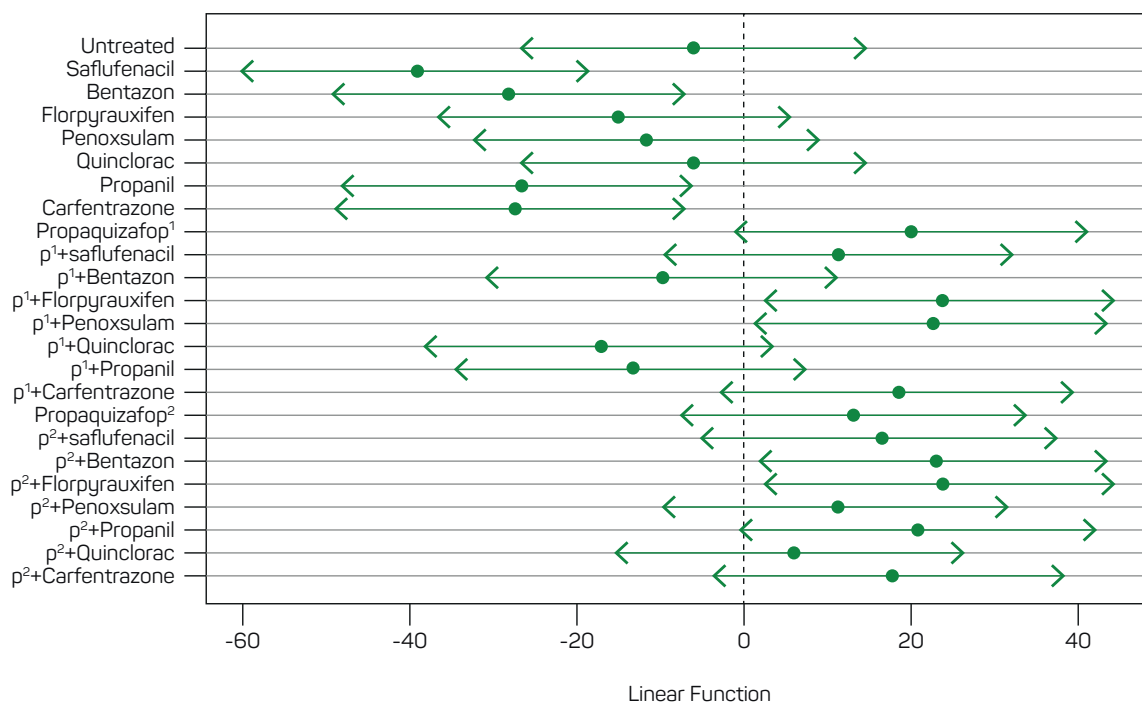
Means followed by the same letter do not differ from each other according to the Scott-Knott test ($p \leq 0.05$). Uppercase letters compare herbicides within the same dose of propaquizafop; lowercase letters compare propaquizafop doses for a given herbicide

Figure 6 - 1,000-grain weight (g) of irrigated rice subjected to the application of three doses of propaquizafop in a tank mix with different herbicides. Formigueiro, 22/23 season



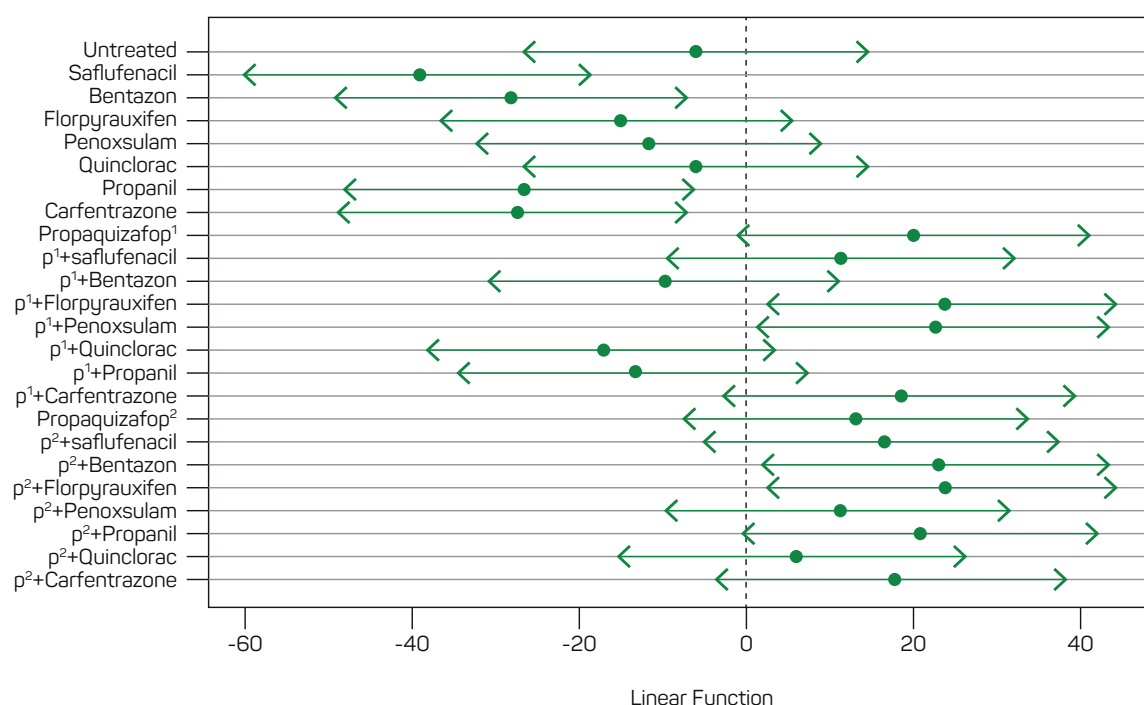
Means followed by the same letter do not differ from each other according to the Scott-Knott test ($p \leq 0.05$). Uppercase letters compare herbicides within the same dose of propaquizafop; lowercase letters compare propaquizafop doses for a given herbicide

Figure 7 - Grain yield (kg ha^{-1}) of irrigated rice subjected to the application of three doses of propaquizafop in a tank mix with different herbicides. Formigueiro, 22/23 season



The dashed line represents additional treatment. Treatments above this line are considered superior, while those below are considered inferior. P¹ propaquizafop 125 g ha⁻¹, P² propaquizafop 180 g ha⁻¹

Figure 8 - Dunnett's test comparing all treatments to the additional treatment, which consisted of sequential application of propaquizafop (125 g ha⁻¹) in Dom Pedrito. 22/23 season



The dashed line represents additional treatment. Treatments above this line are considered superior, while those below are considered inferior.

P¹ propaquizafop 125 g ha⁻¹; P² propaquizafop 180 g ha⁻¹

Figure 9 - Dunnett's test, comparing all treatments to the additional treatment, which consisted of sequential application of propaquizafop (125 g ha⁻¹) in Formigueiro. 22/23 season

In Dom Pedrito, the treatments with bentazon, saflufenacil, propanil, and carfentrazone alone had lower yields compared to the additional treatment, which obtained 3,233 kg ha⁻¹ of yield (Figure 8). Additionally, the tank mix with bentazon, quinclorac, and propanil with the lower rate of propaquizafop resulted in lower yields than the additional treatment, although there was no statistical difference due to the overlap of confidence intervals (Figure 8). The results suggest that antagonism promoted by some tank mixes can be minimized by alone application sequential of propaquizafop. The tank mixes with florpyrauxifen at the two rates of propaquizafop had higher yield than additional factor, mainly due to broad spectrum of control and additive interaction (Figure 8).

An additive response was observed between the tank mix of quizalofop and quinclorac, carfentrazone or thiobencarb, with yields did not differ from the treatment with quizalofop alone (Rustom et al., 2019), as observed in the present study. Furthermore, the application of quizalofop with propanil or 3 days after application of ACCase may result in reductions in rice yield (Rustom et al., 2020), as collected for both sites (Table 3 and 4).

It should be noted that the average yield of the treatments that stood out most in Dom Pedrito was around 6000 kg ha⁻¹, below the average for Rio Grande do Sul of 8790 kg ha⁻¹ (Companhia Nacional de Abastecimento, 2023). This may be a result, among other factors, of the high temperatures faced by the crop at the time of flowering, which cause sterility of the spikelets (Yoshida, 1981).

In Formigueiro, the Dunnet test showed that the herbicides applied alone let to lower yields than the additional treatment, which yield 7,878 kg ha⁻¹, except for quinclorac and propaquizafop (Figure 9). Tank mix had yields similar or higher than the additional treatment, except for propaquizafop plus propanil (Figure 9).

The application of propaquizafop with broad-leaf spectrum herbicides proved to be a viable option for producers, expanding the control spectrum and allowing only one application, thus reducing costs. However, care should be taken as to which herbicides to use, since propanil is an antagonistic mixture and should be avoided. Furthermore, further studies could be conducted to evaluate other herbicides, especially auxin mimics.

4. Conclusions

Tank mix of propaquizafop with other herbicides used in flooded rice for broadleaf weed control can be used to increase the spectrum of action of the herbicides. Mixtures with carfentrazone, bentazon, penoxsulam, florpyrauxifen, quinclorac, and saflufenacil result in additive interaction and are an alternative for use in rice with propaquizafop tolerance. Tank mix of propaquizafop with propanil are antagonistic, reducing control of barnyardgrass and weedy rice and grain yield of flooded rice, and should not be used.

Author's contributions

The authors equally contributed to the completion of this work.

Acknowledgements

The authors would like to thank UruAgro Assessoria Agropecuária for its assistance during the conduct of the experiments, and the producers Thiago Bolson and Celso

Ricardo Mario for providing the area for conducting the experiments.

Funding

The authors would like to thank the National Council for Scientific and Technological Development (CNPq) and the Coordination for the Improvement of Higher Education Personnel (Capes) for granting research grants to conduct the work.

References

- Adama Brasil. [Acert herbicide label: registration with MAPA n° 2093]. Londrina: Adama; 2024[access Mar 23, 2024]. Available from: https://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons
- Agostinetto D, Ulguim AR, Vargas L. [Weed management in a no-tillage system]. In: Aldeia Norte, editor. [No-tillage system in Brazil]. Passo Fundo: Aldeia Norte; 2022[access nov 16, 2023]. Available from: <http://www.alice.cnptia.embrapa.br/alice/handle/doc/1149870>
- Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. Köppen's climate classification map for Brazil. Meteorol Z. 2013;22(6):711-28. Available from: <https://doi.org/10.1127/0941-2948/2013/0507>
- Avila LA, Marchezan E, Merotto A, Menezes VG, Andres A, Goulart ICGR et al. Status of weedy rice (*Oryza* spp.) infestation and management practices in southern Brazil. Weed Sci. 2021;69(5):536-46. Available from: <https://doi.org/10.1017/wsc.2021.24>
- Barbieri GF, Ulguim AR, Pereira GR, Avila LA, Goulart ICGR, Vargas L et al. Herbicide mixtures: interactions and modeling. Adv Weed Sci. 2022;40(spe1):1-25. Available from: <https://doi.org/10.51694/AdvWeedSci/2022;40:seventy-five011>
- BASF Corporation. Provisia™ production system. Ludwigshafen: BASF Corporation; 2024[access Jan 11, 2024]. Available from: https://agriculture.basf.com/br/pt/protecao-de-cultivos-e-sementes/produtos/provisia.html?utm_source
- Bianchi L, Galon L, Ferreira EA, Vargas L, Andres A, Silva AFM et al. Effects of glyphosate and clethodim alone and in mixture in sourgrass (*Digitaria insularis*). Crop Prot. 2020;138. Available from: <https://doi.org/10.1016/j.cropro.2020.105322>
- Colby SR. Calculating synergistic and antagonistic responses of herbicide combinations. Weeds. 1967;15(1):20-2. Available from: <https://doi.org/10.2307/4041058>
- Companhia Nacional de Abastecimento – Conab. [Grain bulletin]. Brasília: Companhia Nacional de Abastecimento; 2023[access: Dec 02, 2023]. Portuguese. Available from: <https://www.conab.gov.br/info-agro/safras/graos>
- Counce PA, Keisling TC, Mitchell AJ. A uniform, objective, and adaptive system for expressing rice development. Crop Sci. 2000;40(2):436-43. Available from: <https://doi.org/10.2135/cropsci2000.402436x>
- Fruet BL, Merotto A, Ulguim AR. Survey of rice weed management and public and private consultant characteristics in Southern Brazil. Weed Technol. 2020;34(3):351-6. Available from: <https://doi.org/10.1017/wet.2019.115>
- Gazziero DLP. [Mixtures of pesticides in tank, in Brazilian farms]. Planta Daninha. 2015;33(1):83-92. Portuguese. Available from: <https://doi.org/10.1590/S0100-83582015000100010>
- Goulart ICGR, Avila LA, Merotto A, Vargas L, Bianchi L. Distribution of weedy red rice (*Oryza sativa*) resistant to imidazolinone herbicides and its relationship to rice cultivars and wild *Oryza* species. Weed Sci. 2014;62(2):280-93. Available from: <https://doi.org/10.1614/WS-D-13-00126.1>
- Healy MJR. The analysis of a factorial experiment with additional treatments. J Agric Sci. 1956;47(2):205-6. Available from: <https://doi.org/10.1017/S0021859600040120>
- Heap I. The international herbicide-resistant weed database. Weeds. 2024[access Jan 11, 2024]. Available from: www.weedscience.org
- Hinga M, Jang S, Taylor S, Mohr D, Gibbons M. Methods and compositions to produce rice resistant to ACCase inhibitors. United States Patent US9370149B2. 21 Jun 2016[access Jan 11, 2024]. Available from: <https://patents.google.com/patent/US9370149B2/en>
- Lancaster ZD, Merotto A, Vargas L, Goulart ICGR, Bianchi L. Evaluation of quizalofop tank-mixtures for quizalofop-resistant rice. Crop Prot. 2019;116:7-14. Available from: <https://doi.org/10.1016/j.cropro.2018.10.004>
- Menezes VG, Goulart ICGR, Merotto A, Vargas L. Red rice (*Oryza sativa*) resistant to the herbicides imidazolinones. Planta Daninha. 2009;27(spe):1047-52. Available from: <https://doi.org/10.1590/S0100-83582009000500018>
- Ottis BV, Mattice JD, Talbert RE. Determination of antagonism between cyhalofop-butyl and other rice (*Oryza sativa*) herbicides in barnyardgrass (*Echinochloa crus-galli*). J Agric Food Chem. 2005;53(10):4064-8. Available from: <https://doi.org/10.1021/jf050006d>
- Polito RA, Merotto A, Vargas L, Goulart ICGR, Bianchi L, Oliveira F et al. Interaction of acetyl-CoA carboxylase enzyme inhibiting herbicides with auxin herbicides on ryegrass. Cienc Rural. 2021;51(4):1-12. Available from: <https://doi.org/10.1590/0103-8478cr20200462>

- R Core Team. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing; 2019.
- RiceTec. Research technology. Alvin: RiceTec; 2024[access Jan 10, 2024]. Available from: <https://www.ricetec-sa.com/site/tecnologia-em-pesquisa/>. Accessed: Jan 2024.
- Richter GL, Andrade Júnior AS, Goulart ICGR, Merotto A, Vargas L. Introducing rice yield loss caused by weed competition into the SimulArroz model. *Pesq Agropec Bras*. 2019;54:1-12. Available from: <https://doi.org/10.1590/S1678-3921.pab2019.v54.01418>
- Rustom SY, Merotto A, Goulart ICGR, Vargas L. Evaluation of sequential applications of quizalofop-p-ethyl and propanil plus thiobencarb in acetyl-CoA carboxylase inhibitor-resistant rice. *Weed Technol*. 2020;34(4):506-10. Available from: <https://doi.org/10.1017/wet.2020.9>
- Rustom SY, Merotto A, Goulart ICGR, Vargas L. Interactions of quizalofop-p-ethyl mixed with contact herbicides in ACCase-resistant rice production. *Weed Technol*. 2019;33(2):233-8. Available from: <https://doi.org/10.1017/wet.2018.116>
- Sanders TL, Goulart ICGR, Merotto A, Vargas L, Rustom SY. Evaluation of sequential applications of quizalofop-P-ethyl and florypyrauxifen-benzyl in acetyl CoA carboxylase-resistant rice. *Weed Technol*. 2021;35(2):258-62. Available from: <https://doi.org/10.1017/wet.2020.114>
- Silva AL, Merotto A, Goulart ICGR, Vargas L. Surveys of weed management on flooded rice yields in southern Brazil. *Weed Sci*. 2021;70(2):249-58. Available from: <https://doi.org/10.1017/wsc.2021.77>
- Silva AL, Merotto A, Goulart ICGR, Vargas L. Weed phytosociology survey in flooded rice cultivated on Clearfield® system. *Rev Bras Herbic*. 2020;19(3):1-9. Available from: <https://doi.org/10.7824/rbh.v19i3.724>
- Ulguim AR, Goulart ICGR, Merotto A, Vargas L, Bianchi L. Understanding nutrient competition between *Echinochloa* spp. and *Oryza sativa* L. *J Plant Protect Res*. 2020;60(3):296-310. Available from: <https://doi.org/10.24425/jppr.2020.133320>
- Ulguim AR, Merotto A, Vargas L, Goulart ICGR, Bianchi L. Resistance mapping of the genus *Cyperus* in Rio Grande do Sul and selection pressure analysis. *Planta Daninha*. 2019;37:1-8. Available from: <https://doi.org/10.1590/S0100-83582019370100062>
- United States Department of Agriculture – USDA. Soil classification. Washington: United States Department of Agriculture; 2024[access May 26, 2024]. Available from: <https://www.nrcs.usda.gov/resources/guides-and-instructions/soil-classification>
- Yoshida S. Fundamentals of rice crop science. Los Baños: The International Rice Research Institute; 1981.